

# PROBLEMS WITH ROCK CLASSIFICATION FOR EMPIRICAL AND NUMERICAL DESIGN

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## ABSTRACT

Most empirical and numerical approaches to design in rock mechanics incorporate rock mass classification. Numerical design methods generally use classification values to calculate input parameters for stress-based failure criteria. Empirical methods use classification to allow comparisons between similar rock mass conditions, generally based on a graphical design technique that differentiates stable and failed opening geometries.

Classification systems are the best tool available for assessing rock mass properties; however, there are problems with classification systems that should be highlighted. Rock mass performance can only be realistically estimated by coupling a unique description of the rock mass with known loading conditions. Current classification systems cannot provide a unique classification value. The weightings applied to quantify rock mass properties for classification can result in significantly different rock masses having the same classification values. These weightings have been proven effective for tunnel design and support, but classification systems are now used for many more applications.

Rock classification systems evolved from a quick and easy field tool for estimating tunnel stability and support requirements. The need for a rapid field tool means that rock mass classification is relatively insensitive to improved methods of measuring rock mass properties.

Problems with classification systems and their application are highlighted in this paper. These problems must be recognized and documented before improvements can be made. An understanding of the evolution of classification systems and their application for both numerical and empirical design approaches is invaluable in highlighting current shortcomings.

## INTRODUCTION

Rock mass classification systems are the basic component of empirical mine design. They have been traditionally used to group areas of similar rock mass properties, to provide guidelines for stability performance, and to estimate support requirements. More recently, rock

mass classification values have been used along with numerical modeling tools. Substantial work has been done linking classification values to various material properties such as Young's modulus, as well as "m" and "s" for Hoek-Brown failure criteria and "φ" and "c" for Mohr-Coulomb criteria. These values are then used as input for numerical models.

There are many rock mass classification schemes, often developed for site-specific purposes. The most commonly used systems are the Rock Quality Designation (RQD) [Deere et al. 1967], forms of the Rock Mass Rating (RMR) system developed by Bieniawski [1973, 1976, 1979, 1989], and the Norwegian Geotechnical Institute's Q-system [Barton et al. 1974]. The RQD system is a measure of joint spacing and is incorporated as part of both the Q and RMR systems. More recently, the Geological Strength Index (GSI), which has evolved from the RMR system, is being used [Hoek et al. 1995]. The Q, RMR, and GSI systems are discussed in this paper.

There are problems and challenges with rock mass classification systems, primarily due to their numerous and conflicting goals. Initially, classification was done to give a quick and repeatable assessment of the rock mass to provide guidelines for underground opening stability and support requirements. It was made quick and easy to use by limiting the number of rock mass classification categories. A need for greater precision in the estimation of opening stability and support led to an increase in possible classification categories, resulting in increased time needed for classification and increased difficulty in obtaining repeatable results. An additional challenge for rock mass classification is the goal of providing an accurate assessment of rock mass behavior and properties for an increasing array of engineering applications. These include:

- Tunnel and mine opening stability assessments
- Tunnel and mine opening support requirements
- Rock mass properties, including Young's modulus, Poisson's ratio, and strength
- Rock mass failure criteria
- Rock mass slope stability, as well as other varied applications

This paper summarizes some of these issues and suggests approaches for improving the application of field data for rock mechanics.

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## ROCK CLASSIFICATION VERSUS CHARACTERIZATION

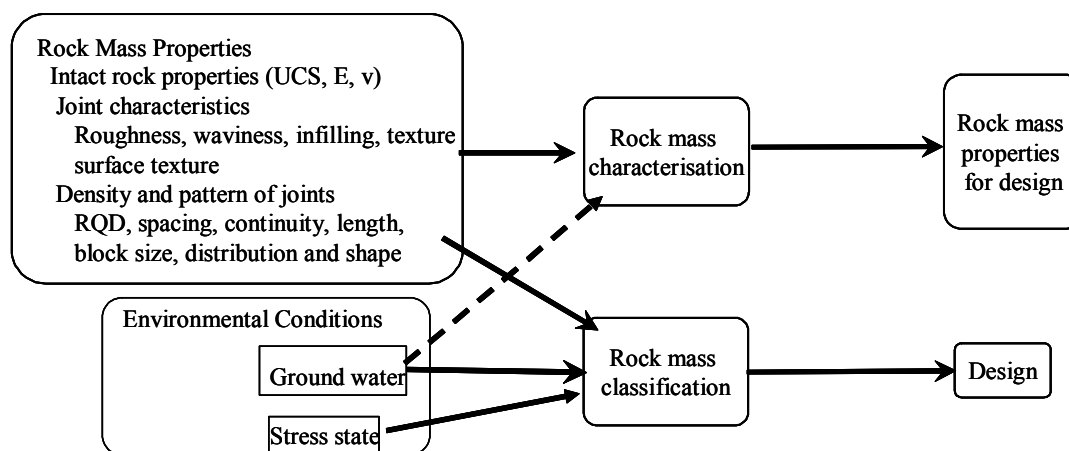
Rock classification is used for many purposes in rock mechanics. Classification systems were originally developed as complete design packages for civil engineering tunnel applications. Given the rock mass classification value and tunnel span, support requirements and estimated tunnel stability could be obtained [Barton et al. 1974; Bieniawski 1976]. These classification systems often included factors to assess stress conditions and the orientation of discontinuities relative to the engineered structure. One of the main differences between tunneling and mining applications of rock classification is the large variation in orientation, depth, and geometry of underground openings in mining. Civil engineering applications are generally applied to tunnels at a fairly constant depth, orientation, and geometry. None of these conditions is constant in most mining applications.

If mining applications included joint orientation and stress conditions in rock classification, the same rock mass could have dozens of classification values throughout the mine depending on the drift orientation, mining level, and the excavation history [Milne et al. 1998]. This would lead to significant confusion and make the classification systems useless. Components of classification systems are often used in empirical mine design applications, with site-specific or stress conditions assessed separately. Numerical design methods also often apply stress conditions with the design process, so the addition of stress factors within the classification system is redundant. Both the RMR and Q classification systems are frequently adjusted for mining applications. The  $Q'$  system is used in numerous empirical design techniques and differs from the  $Q$ -system in that the stress reduction factor (SRF) is set to 1.0 [Potvin 1988; Clark 1998]. RMR' system is often used for mining span

design. The RMR' system does not include the RMR correction for joint orientation.

Palmström et al. [2001] discuss the difference between rock classification and characterization. Rock mass characterization should consist of the intrinsic properties of the rock mass, which include intact rock properties, discontinuity spacing and pattern, as well as discontinuity properties. If rock characterization is used, loading or environmental factors such as stress or discontinuity orientation should be considered later in the design process. Rock classification systems, however, should be treated as complete design packages and are to be used with the appropriate empirical design charts (Figure 1).

There has been some discussion concerning the assessment of groundwater factors in rock mass classification and characterization. Palmström et al. [2001] suggested that groundwater be excluded from rock mass characterization and added later in the design process since water conditions can vary significantly in the same rock mass. Laubscher and Taylor [1976] incorporated water as a factor, reducing the strength properties on the discontinuity surfaces in their modified RMR system (MRMR). There is also some confusion as to the application of water conditions with the stability graph design method for underground openings [Potvin 1988]. Hoek et al. [1995] state the following concerning the application of  $Q'$  for the stability graph method: "The system has not been applied in conditions with significant groundwater, so the joint water reduction factor  $J_w$  is commonly 1.0." The groundwater term in the  $Q'$  classification is often ignored when using the stability graph design method. This is not a safe approach because there is nowhere else to assess groundwater conditions in this design method. Similar confusion exists with determining "m" and "s" failure criteria for design [Hoek and Brown 1980]. The original "m" and "s" factors were based on RMR<sub>76</sub> classification values, with



<sup>1</sup>Discrete features such as faults and shears are not generally assessed in rock classification schemes.

<sup>2</sup>Ground water has been considered either a rock mass property or an environmental or loading condition.

Figure 1.—Components of rock classification and rock characterization (after Milne and Hadjigeorgiou [2000] and Cai et al. [2004]).

the groundwater factor set to dry conditions [Hoek et al. 1995]. This was done to avoid counting groundwater conditions twice. It assumes that effective stress conditions will be used with numerical modeling “m” and “s” design approaches.

Groundwater conditions are not intrinsic properties of the rock mass and, ideally, groundwater would be assessed later in the design process. Unfortunately, there are few empirical or numerical design techniques that allow groundwater conditions to be added to the design process. It is not safe to remove groundwater from rock mass characterization unless it is known that the groundwater conditions will be assessed later in the design process. As a general rule, any factors known to influence stability should be included in either the rock characterization or the design process.

### QUALITATIVE VERSUS QUANTITATIVE ROCK MASS CHARACTERIZATION

One of the goals of classification systems is that they be a quick assessment of rock mass conditions for support design and stability assessment. A second goal of rock classification is to obtain repeatable results. The repeatability of rock classification can be achieved by assessing the rock mass in very broad, general categories at the cost of precision or by assessing the parameters that make up rock classification systems with quantitative measurements at the cost of speed and ease of use.

One of the earliest rock mass classification systems is attributed to Terzaghi [1946], who states: “From an engineering point of view, knowledge of the type and intensity of the rock defects may be much more important than the type of rock which will be encountered.” Terzaghi’s classification uses terms such as “moderately blocky and seamy” to describe the rock mass and is difficult to assess accurately due to its subjective description of the rock mass. This system was probably easy to use. There were, however, only seven categories of rock masses ranging from intact rock to swelling rock containing clays such as montmorillonite, so it could not be an overly precise assessment of ground conditions.

Modern classification systems, such as the Q and variations of the RMR systems, consist of assessments of the size and perhaps shape of intact blocks of rock bounded by discontinuities, the discontinuity surface condition or frictional properties, intact rock strength, and groundwater conditions.

The method of assessment of these categories has evolved from the mainly subjective assessment of factors in Terzaghi’s classification to more qualitative assessments. The RMR system is based on a numerical assessment of five parameters:

- Intact rock unconfined compressive strength (UCS)
- Rock Quality Designation (RQD)
- Discontinuity spacing
- Discontinuity surface condition and
- Groundwater

Intact rock strength, RQD, and groundwater are assessed in fairly quantitative terms. The discontinuity assessment term is more subjective and contains descriptions such as “very rough surfaces” and “slightly rough surfaces,” which require experience to differentiate between and do not provide a very precise assessment.

The Q classification system is probably the least subjective classification currently in common use. The more analytical and quantitative descriptions used in the Q-system are coupled with an assessment of more rock mass parameters, and these assessments are divided into many more categories. For instance, the RMR<sub>76</sub> system describes the condition of discontinuities with five broad categories. The Q-system, with its assessment of small- and large-scale roughness, alteration, and infilling can differentiate between more than 60 conditions of joint surfaces. The Q-system can give very precise rock classification values; however, this results in making repeatability more difficult to achieve and also increases the time required to obtain an estimate of rock classification.

The RMR system has evolved to give the user the option of estimating rock classification values with more precision. The RMR<sub>89</sub> system is the best example. It allows the user to use the same five categories assessing discontinuity surface conditions, but adds the option of describing joint surface conditions with five properties for assessment, which are:

- Discontinuity length;
- Discontinuity aperture or separation;
- Discontinuity roughness;
- Discontinuity infilling; and
- Discontinuity weathering

Each of these 5 properties is broken down into 5 categories, giving a total of 25 possible joint surface assessments, compared to 60 categories in the Q-system and 5 with RMR<sub>76</sub>.

The GSI system is the newest commonly used rock mass classification system. It makes a conscious attempt to move away from classification systems that quantify or rate individual properties of the rock mass. The RMR classification system has evolved to be more quantifiable [Bieniawski 1989], and others have attempted to improve rock mass characterization by improving our ability to measure rock mass properties such as discontinuity surface properties [Milne et al. 1991; Hadjigeorgiou et al. 1994] and intact block size distributions [Hadjigeorgiou et al. 1998]. In his discussion of the development of the GSI

classification system, Hoek [2004] states: “It was also felt that a system based more heavily on fundamental geological observations and less on ‘numbers’ was needed.” The GSI classification system consists of six categories describing the size and shape of intact rock blocks and five categories describing the surface condition of discontinuities. This system is based on geological observations and avoids the engineering approach of dividing the properties of a rock mass into components and measuring these components as accurately as possible.

The GSI system has been developed to provide rock mass properties for numerical modeling, which may account for the different approach taken for assessing the rock mass. Practitioners are encouraged to avoid precise estimates of classification, but rather to give a range representative of the highly variable properties found in natural materials such as rock masses. This approach is also well suited to numerical modeling, where more precise estimates of rock mass properties may rely on back analysis of observed rock mass behavior.

The following section discusses input for classification systems.

## INPUT PROPERTIES FOR ROCK MASS CHARACTERIZATION

Goals of conventional classification systems include quickly obtaining as precise and repeatable an estimate of rock characterization values as possible. These goals are, to a certain extent, contradictory. Increased precision is difficult to duplicate, especially by different practitioners. An approach taken with some systems has been to break the properties of a rock mass into more easily quantified components, which improves the precision and repeatability, but may significantly increase time required to conduct rock characterization. A discussion of the more common components of rock mass characterization follows.

### Intact Rock Strength

Intact rock strength is included in all versions of the RMR system. It is an intrinsic part of rock mass characterization; however, in many systems like Q' and GSI, the rock strength assessment is left for the design process.

### Groundwater Conditions

Groundwater conditions are part of most classification systems, such as Q, Q', and RMR. If groundwater is not implicitly included in the design, it must be included in the rock mass classification/characterization. The conventional characterization systems assign a weighting to groundwater conditions based on categories such as—

- Dry conditions;
- Damp conditions;
- Water inflow in liters per minute along 10 m of drift; or
- A description or measurement of water pressure.

These descriptions of groundwater conditions seem sufficiently precise and easily quantified for rock characterization purposes. The GSI system does not include water in its basic classification, so it should be treated later as a correction or assessed in the design procedure used.

### Discontinuity Spacing and Intact Geometry

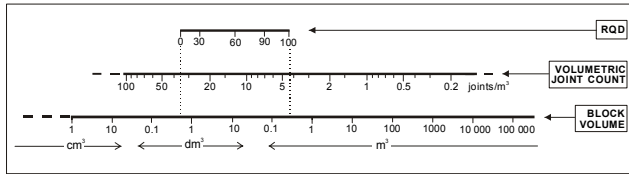
The rock mass RQD is used in both the RMR and Q classification systems to assess discontinuity spacing. The actual spacing of discontinuities is included with RMR, and Q looks at the number of joint sets present. The RQD assessment of spacing has significant drawbacks [Milne et al. 1998]. It is sensitive to the measuring direction; however, this can be corrected by using the equation by Palmström [1985] that relates the number of joints found in a cubic meter of rock ( $J_v$ ) to an average RQD:

$$RQD = 115 - 3.3 J_v \quad (1)$$

Other problems with the RQD term include the fact that it is relatively insensitive to discontinuity spacings greater than 30 cm. The RMR system corrects for this by adding a measurement of discontinuity spacing. The Q-system couples RQD with an assessment of the number of joint sets present ( $J_n$ ). It can easily be shown, however, that if three joint sets with equal spacing are present in a rock mass, the ratio of  $RQD/J_n$  becomes a constant at a joint spacing of greater than 0.7 m.

The assessment of joint spacing in classification systems is an attempt to indirectly define block size. Line mapping provides much of the data required for rock mass characterization and can provide realistic estimates of intact block size geometry. There is little justification for discarding much of the data collected by mapping programs simply because the data cannot be applied to currently used rock classification systems. Mapping data can generate realistic three-dimensional discontinuity systems, which can be used to develop more complete information, such as block size distribution, that better represent the discontinuous nature of a rock mass. Based on field work in several underground mines, Hadjigeorgiou et al. [1998] have shown that three-dimensional joint systems can provide a better estimate of block size than that provided by traditional rock classification systems. Figure 2 shows a correlation between RQD, block size, and the  $J_v$  term.

The actual geometry of intact blocks is not included in these systems; however, it is discussed in the GSI system, and other rock mass characterization systems, such as RMI



**Figure 2.—Correlation between RQD, block size, and the joint volume term,  $J_v$ .**

[rockmass.net 2007], include an assessment of intact block geometry.

## DISCONTINUITY SURFACE CONDITION

The surface condition of discontinuities is a measure of how easily blocks can move relative to each other and is an important component of rock characterization. The Q-system has one of the most precise approaches for assessing this property and looks at it in terms of the following:

- Large-scale roughness
- Small-scale roughness
- Alteration
- Infilling thickness

The RMR<sub>89</sub> system adds terms describing infilling aperture and length. There is some difficulty assessing the Q terms for roughness and alteration, and guidelines have been developed to assist with this.

The following discussion is taken from Milne and Hadjigeorgiou [2000] and Milne et al. [1992]. In the RMR system, joint roughness is part of the discontinuity description, with no distinction between small- and large-scale roughness. The Q-system identifies two scales of joint roughness as distinct input into  $J_r$ . No qualitative methods of assessing roughness are included with the original classification methods; however, less subjective approaches have been applied to classification.

A study was conducted to improve the precision and repeatability possible for estimating values of joint roughness for the Q classification system. An extensive field data-gathering program was conducted to obtain discontinuity profiles using a 1-m-long “profile comb” (Figure 3) [Milne et al. 1991]. Based on the collection of more than 200 1-m-long discontinuity profiles from 10 mines across Canada, a simple repeatable field-measuring technique has been developed. The joint roughness coefficient (JRC) [Barton and Choubey 1977], coupled with these field data, has been applied to assess small-scale roughness for 10-cm profile lengths. Based on these field data, a JRC value of less than 10, or a joint profile amplitude of less than 2.5 mm over a 10-cm length, is defined as “smooth.” For JRC estimates greater than 10 and amplitudes greater than 2.5 mm, surfaces are defined as “rough.” A small-scale roughness term,  $J_r/r$ , is used to

represent small-scale roughness and is set to 1.0 and 1.5 for smooth and rough joints, respectively. For large-scale waviness,  $J_r/w$ , three categories of waviness have been defined based on field data on profile amplitudes over a 1-m length. Wavy joints have 1-m profile amplitudes of 20 mm or more, and the  $J_r/w$  value is set to 2.0. Planar to wavy joints have amplitudes between 10 and 20 mm and a  $J_r/w$  value is set to 1.5. To obtain a  $J_r$  value for the Q classification, the  $J_r/r$  and  $J_r/w$  values are multiplied together (Equation 2).

$$J_r = J_r/r \times J_r/w \quad (2)$$

Developing more quantitative assessments of rock mass classification systems is more complicated than simply developing improved methods of measuring rock mass properties and superimposing them on existing subjective descriptions. Improved measuring methods must be based on extensive field data collections and should ideally be coupled with a database of case histories.

## Summary of Input Parameters for Existing Rock Classification Systems

More detailed data on rock classification can be applied to some aspects of existing classification systems. In many cases, however, it would be difficult to know how to incorporate detailed information with existing classification. As an example, it is difficult to know how a measure



**Figure 3.—One-meter-long profile comb used to measure discontinuity roughness at 10 mines across Canada.**

of the rock mass block size can be incorporated with current systems that assess the rock mass in terms of joint spacing, RQD, and the number of discontinuity sets present. Work has been done to augment the GSI classification system with more quantifiable terms [Cai et al. 2004]; however, it could be argued that the GSI system was specifically developed to avoid this approach.

The challenges with developing a more precise method of quantifying properties of a rock mass are overshadowed by problems with how classification systems use these data. Classification systems attempt to assess factors influencing rock mass performance and properties and represent that assessment as a single number. To do this, individual rock mass properties are given a weighting, which represents the relative importance of that rock mass property. The next section discusses the importance of these weightings.

### WEIGHTING ASSESSMENTS OF ROCK MASS PROPERTIES

Classification systems attempt to provide a basis for estimating deformation and strength properties for a rock mass, as well as provide data for estimating support requirements [Cai et al. 2004]. They are also used to assist in estimating the overall stability of excavations. To obtain a single classification/characterization value to represent a rock mass, weightings are given to the various rock mass properties. The weightings assigned to the individual properties of a rock mass are, in most cases, the same under all loading conditions. Table 1 summarizes some of these weightings expressed as the influence of each property on the total range in classification values. The assignment of a weighting, or degree of influence, is required to allow an engineer to represent rock mass properties as a single number. This is a significant weakness in rock mechanics. Apart from a fairly major change between the RMR<sub>76</sub> and RMR<sub>89</sub> systems, these weightings have not changed significantly since the early 1970s. The GSI system seems to differ; however, the main difference is that rock strength and groundwater conditions are left for later consideration. The remaining properties of block size and discontinuity condition are given weightings similar to those in the Q-system.

The application of weighting systems within classification schemes means that a rock mass with a relatively large intact block size and smooth slippery joint surfaces can have the same classification value as a rock mass with much smaller intact blocks and rough joints. Table 2 gives an example of two different rock masses (A and B) with different properties, but similar rock mass classification values.

**Table 1.—Influence of rock mass properties on rock classification (after Milne and Hadjigeorgiou [2000])**

	Classification system				
	Q'	Q	RMR <sub>76</sub>	RMR <sub>89</sub>	GSI
Unconfined compressive strength (UCS)					
% of total range.....	0	0	16	16	0
Block size					
% of total range.....	41	33	46	35	50
Discontinuity surface friction					
% of total range.....	38	30	27	33	50
Groundwater					
% of total range.....	21	17	11	16	0
Stress or UCS/stress ratio					
% of total range.....	0	20	0	0	0

**Table 2.—Classification assessment of two different rock masses**

	Rock mass A	Rock mass B
UCS.....	75 MPa	75 MPa
Groundwater .....	Dry	Dry
RQD .....	100%	20%
No. of joint sets.....	2 joint sets	3 joint sets
Average joint spacing.....	2-m spacing	10-cm spacing
10-cm scale JRC.....	<10	>10
Amplitude over 1 m .....	<1 cm	>3 cm
Alteration .....	Chlorite coating, can be dented with a fingernail	Clean joint surfaces
Q'.....	≈ 6	≈ 6
GSI.....	≈ 60–65	≈ 60–65
RMR <sub>76</sub> .....	≈ 74	≈ 55
RMR <sub>89</sub> .....	≈ 77–82	≈ 63

Rock mass A and rock mass B would require significantly different support measures, and it is unlikely that maximum stable tunnel spans or the overall strength or deformation modulus of these two rock masses would be the same. Neither the Q' nor GSI systems reflect this difference. Different variations in discontinuity spacings and conditions could have been chosen to give the same RMR classification values for similar differences in rock mass properties.

The influence of loading conditions and scale effect are two other factors that can have significantly different effects on the performance and properties of the two rock masses described. In a narrow tunnel situation with a span in the order of 3 m, rock mass A would, in most cases, perform much better than rock mass B. Very few intact rock blocks would be exposed in rock mass A, so the intact rock properties would have a greater influence on the overall rock mass compared to rock mass B.

It seems unrealistic to assume that the weightings applied to rock mass parameters will give accurate assessments of stability and rock mass properties at all scales of engineering applications and at all loading conditions. The Q-system reflects the importance of loading conditions with the assessment of intact rock strength. Intact rock strength is included in the SRF factor, and when the UCS

of the intact rock divided by the induced stress exceeds 10, rock strength is not a factor in rock classification. Underground engineering structures range in size from drill holes to small tunnels to open stopes hundreds of meters in extent. It may be necessary to apply some scaling factor to rock classification assessments of intact block geometry to account for the scale of engineering applications.

The inherent weakness in the weighting factors applied in rock classification schemes can be illustrated with some typical design applications using some empirical design methods.

### **Tunnel Roof Design**

Both the Q classification system and the RMR<sub>76</sub> system were originally developed to assess the stability, standup time, and support requirements of tunnels. Most of the rock mass properties, environmental conditions, and project-related features shown in Figure 1 are combined in some fashion to determine an empirical tunnel design. The success of these empirical design methods implies that all of the features used in the design process do actually influence tunnel stability.

### **Pillar Design**

There are many empirical pillar design approaches. Commonly used empirical design methods include those developed by Hedley and Grant [1972], Hudyma [1988], and Lunder [1994]. It is interesting to note that none of these empirical design approaches, based on more than 17 mines and a wide range of rock mass properties, use any rock mass classification assessment as a factor influencing stability. These design methods rely only on the UCS of the rock, pillar geometry, and stress induced in the pillars.

### **Stope Hanging Wall Design**

Stope hanging wall stability involves large rock surfaces, often several thousands of square meters in extent. There are several empirical techniques used for estimating the stability and dilution of large stope hanging walls. The most commonly used empirical design methods are versions of the stability graph and dilution graph [Potvin 1988; Nickson 1992; Clark 1998; Capes et al. 2005]. These design techniques have gained widespread application and rely upon a modified version of Barton's rock quality Q classification system coupled with assessments of induced stresses, joint orientation and surface orientation, and hanging wall geometry. With this design method, neither the rock strength nor the induced stress influence the assessment of the relaxed, low-stress hanging wall condition. This indicates that the data collected for developing the design method were not sensitive to the induced stresses or rock strength [Wang et al. 2007].

## **CONCLUSIONS**

Rock mass classification and characterization systems are the best tools available for assessing rock mass properties. They were designed to be easily used assessments of the properties believed to be most important for estimating the performance of excavations in rock. Most classification systems were originally developed for civil engineering tunnel design. The application of these systems has greatly increased to areas such as slope stability design and for providing rock mass property input for numerical modeling. Major problems in rock classification and characterization stem from their ease of use and their increasingly wide application.

The easy use of classification systems allows field engineers to quickly make support recommendations while a tunnel is being driven. This original goal for rock classification systems makes them insensitive to improved rock mechanics data. As an example, consider a clean, rough, and wavy joint surface. It would have a Q assessment of  $J_r/J_a$  equal to 3.0 and an RMR<sub>76</sub> assessment of 20. Based on the original classification guidelines, field data estimating JRC, joint amplitude, and joint surface strength would have little or no influence on the classification values. Also, lab tests on discontinuities or even in situ shear tests would also have no effect on the classification values. Some attempts have been made to improve the sensitivity of classification systems to improved data, but this work has not become the industry standard, or even a widely recognized goal.

The process of determining a single number to represent a rock mass classification value necessitates that a weighting system be applied to assess the relative importance of rock strength, block size and geometry, and discontinuity strength. These weighting systems have proven to be effective for assessing support requirements and tunnel back stability. These classification systems now enjoy a wide range of applications and are assumed to be effective at almost any engineering scale and under a wide range of loading conditions. The lack of change in these weighting values over the last 30 years is a reflection of both the accuracy in their initial development as well as the difficulty in making changes to well-used classification schemes. A review of the weighting systems used in rock mass classification is needed.

## **RECOMMENDATIONS**

The individual properties of a rock mass should be assessed as accurately as possible. The relative importance of these individual properties should be determined empirically for a wide range of loading conditions, with a consideration of scale. Empirical data on pillar design suggest that intact rock strength is the only rock mass property that affects pillar stability for a wide range of rock classification values. It may be possible to make significant improvements to design if the individual properties of a

rock mass are considered separately. We cannot expect to obtain good-quality rock mechanics lab and field data on rock mechanics properties unless the commonly used design tools can make use of these data.

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